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Analysis of lithium-ion indirect liquid cooling battery thermal management system with high discharge rate

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ABSTRACT

Electric vehicles are developing rapidly and require technological support. Electric vehicles require good power storage. One of the reasonable parameters of a battery pack is its high discharge capability. A high discharge rate requires suitable cell and heat management capabilities in the battery pack. When discharging, it produces heat energy and needs to be released. The battery thermal management system (BTMS) is a method used to maintain battery heat. BTMS using liquid has a better performance compared to phase-change memory (PCM) and air cooling. The use of liquid coolers still has limitations. Namely, the weight of the cooling system is quite large because of a large amount of liquid which increases the weight of the battery. This study offers the potential to use mini channels mounted on cooling plates for application as BTMS. This research used the finite element method (FEM) process by simulating the process of fluid flow that occurs when the battery is used at various C rates. The results of this study indicate that the type of BTMS can keep the battery hot at working temperatures below 40 ºC.

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1. INTRODUCTION

The limitations of fossil-based energy in terms of sustainability and environmental impact encourage innovations regarding energy sources that are more environmentally friendly and sustainable. Using new and renewable energy sources (RES) is the main focus in dealing with energy problems in the coming years. RES from wind power, sunlight, and geothermal energy has the potential to be developed, and the mix increased [1], [2]. These renewable energies are converted into electrical energy, resulting in increased electrification in various sectors, including transportation. The use of electric vehicles has a variety of positive impacts on the environment, including reducing air and noise pollution in urban areas with high populations. Electric vehicles (EVs) can directly penetrate the existing vehicle market. In other words, implementing EV technology with new and renewable energy sources is one of the focuses in dealing with the limitations of fossil energy. Battery packs are secondary battery cells arranged in series or parallel with the desired specification reference. The battery type greatly influences the battery pack's dimensions or size. Until now, secondary batteries with high energy density and long service life are lithium ion batteries (LIBs) [3]–[7]. LIBs used for battery packs or ESS also contain various main components: cathode, anode, separator, and electrolyte. The cathode material is essential in determining a battery's capacity and energy density. Li-ion diffusion in the solid phase and electrolyte depletion will always limit cell discharge. Significantly, heat is generated within the cell and

dissipates to the environment in all directions. If heat is dissipated only through the graphite at the top of the two electrodes, a temperature gradient will occur along the cell's height, leading to a non-uniform electrode reaction rate [8]. The use of batteries in vehicles, in general, has various challenges, such as the need for batteries that are capable of providing high discharge due to their use in various conditions, such as the need for fast charging and as a provider of energy for supporting devices for electric vehicles such as eddy current brakes and regenerative brakes which require batteries to be able to accept the high load [9]–[11].

One of the problems in a battery that may occur is thermal runaway (TR) caused by an internal short circuit in one cell. If TR spreads to adjacent cells in a battery pack via thermal propagation (TP), it causes havoc and can endanger human life [12]–[14]. TR conditions can be caused by overcharging, internal shorting of cells, and vehicle collisions. However, the cause often occurs when the cell temperature is above a specific limit, allowing a series of exothermic reactions to occur, which will then increase the temperature. If it happens continuously will be the cause of TR. A researcher comprehensively analyzed the characteristics of the TR type 21700 cylindrical lithium-ion battery (LIB) with a specific energy of 266 Wh/kg. Batteries at 30% and 100% state of charge (SOC) are triggered to TR by uniform heating using a flexible heater in a laboratory environment. The correlation between the heat release rate (HRR) and the average flame height of the turbulent spark diffusion was used to estimate the HRR of the LIB. Additional characteristics of cell failure (for cells with 100% and 30% SOC) were also recorded for comparison, including the number of objects removed from the cell, sparks, and subsequent jet fires. An approach was developed to estimate the HRR of a TR-triggered fire, and the results were compared with previous HRR measurements for a 18650 cylindrical cell type with a similar cathode composition [15], [16].

Li-ion batteries have a higher energy density and longer service life than chemical batteries. Li-ion battery performance is still greatly affected by temperature. The optimal temperature is between 15-35 °C, and the maximum temperature difference between modules is below 5 °C. Incorrect temperatures can decrease performance and thermal runaway. A battery thermal management system (BTMS) is needed to avoid thermal runaway when the battery is used. BTMS primarily aims to keep the battery temperature at its optimal temperature, and the battery temperature distribution is even. BTMS, according to the control strategy, can be divided into active and passive cooling systems.

Meanwhile, according to the heat transfer medium, liquid cooling, water cooling, and phase change material (PCM) cooling, The battery thermal management system can be divided into three methods: (a) air-cooled system, (b) liquid-cooled system, and (c) phase change material (PCM) based cooling system. Each method has different characteristics. The cooling effect of the air conditioning system is poor and cannot meet the cooling requirements of the battery if the battery is used in extreme environments or works under high-duty cycles [17]. PCM-based cooling systems effectively reduce temperature and keep temperature differences low, but encapsulation and volume changes during phase changes limit their applicability. Thus, a liquid cooling system can be more suitable for battery thermal management systems [18]–[21]. So far, previous research has focused chiefly on cooling by applying PCM and liquid cooling on the surface area of a cylindrical battery body. A heat potential is focused on the polar area of the battery used. This is the potential to develop a cooler directly in the hot area used. The novelty of this study is to reveal heat transfer in a Li-ion cylindrical battery thermal management system using the indirect liquid cooling method with water as the primary fluid using a cooling plate with a mini channel water flow in the copper tube at the end of the pole used. Most of the research used water or liquid cooling methods using water and some with the PCM method.

2. METHOD

The research process uses a type of cylindrical Li-ion battery. The battery used in this study is a cylindrical type battery with details as in Table 1 with the battery composition cathode, anode, separator, and current collector tabs considered as isotropic so that they can be considered to have the same thermal conductivity and heat value values [22].

Table 1. Properties of the battery cell

Parameter	Value
Nominal voltage (V)	3.2
Nominal capacity (Ah)	2.6
Material cathode	$LiFePO_4$
Dimensions (mm)	26 diameter × 65 height
Cut-off voltage (V)	2.55
Specific heat capacity (J/kg K)	894
Thermal conductivity (W/m K)	Radial: 1.035 Axial/tangential: 14.15

The electrochemical reactions in the anode and the cathode during the charging and discharging processes are shown in (1) and (2) [23]. Definitions of physical phenomena such as the conservation of mass, momentum, and energy equations for heat transfer in this study are as follows [23]:
- Conservation of mass (the continuity equation):

$$\nabla . V = 0 \tag{1}$$

- Conservation of momentum:

$$\frac{\partial(\rho V)}{\partial t} + V.\nabla(\rho V) = -\nabla p + \mu.\nabla^2 V \tag{2}$$

- Conservation of energy:

$$\frac{\partial(\rho C_p T)}{\partial t} + V.\nabla\left(\rho C_p T\right) = \nabla(K\nabla T) = \dot{q} \tag{3}$$

where is the velocity vector, the density of the fluid, the pressure, the dynamic viscosity of the fluid, the volumetric heat generation of the battery, the specific heat, and K is the thermal conductivity.

The battery module's flow field and temperature patterns are affected by the thermal behavior of the battery. It happens when charging and discharging poses take place. Some researchers have conducted an analysis of heat generation levels in batteries. Huang *et al.* [24] and Kung *et al.* [25] studied thermal interaction and heat dissipation of cylindrical Li-ion battery cells. The analysis was carried out by adopting equations for heat generation in battery cells developed by Bernardi *et al.* [26]. Bernardi's equation was used in this study to calculate the generation of heat on the battery, as shown in (4).

$$Q = \frac{1}{V}\left[I^2 R_i + IT\ \frac{dU_0}{dT}\right] \tag{4}$$

Where Q is the battery heat generation rate per unit time and volume, and V is the volume of the battery. I is the current through the battery, $\frac{dU_0}{dT}$ is the internal resistance of the battery cell, is positive in charging and negative in discharging, T is the battery temperature, and is the entropic heat coefficient. The entropic heat coefficient can be set as 0.01116 V. The results of the heat generation rate calculation using (3) are indicated in Table 2.

Table 2. Heat generation at different discharge rates

Discharge rate (C)	Current of the cell (A)	Internal resistance (Ω)	Heat generation rate (W/m³)
0.5	1.75	0.04	1557.315599
1	3.5	0.04	5318.379686
2	7	0.04	19451.75333
3	14	0.04	42400.12092

The study conducted thermal analysis on twenty-five LIBs with discharge rates of 0.5C, 1C, 2C, and 3C with liquid coolants in water. In numerical investigative studies using the finite volume approach. As for the simulation study in the form of a three-dimensional battery module using computational fluid dynamics (CFD). Simulation settings include a pressure-based, laminar/K-epsilon turbulent, incompressible, transient solver. A simple algorithm is used to solve the numerical model and uses a steady operation with 2000 iterations and an element value of 810096 with meshing, as shown in Figure 1, with the inlet set at 25 °C. Figure 1 shows the battery design used in the modeling carried out. The batteries used small segments for analysis. Figure 2 shows the position of the inlet and outlet of the cooling fluid flow. The data collection position is done by sampling in the middle area of the battery module to get an idea of the hottest position. The process carried out in this study was to model the battery pack area provided by BTMS in the form of mini-channel cooling plates made of aluminum. This research is a preliminary process to become the basis for developing mini-channel cooling plates.

The cooler model is an aluminum plate placed in the polar area of the battery used. Inside the plates used, there is a fluid flow pattern made using copper pipes with design details that can be seen in Figure 3. The research process uses scenarios to determine the cooling performance provided by mini-channel cooling plates, as shown in Figure 3. In Figure 3, the process heat flux is applied to the surface of the battery module, representing heat generation from the internal battery. The heat flux obtained is the heat flux when the battery is loaded. The battery uses the SOC range from 90% to 20% for each test.

Figure 1. Battery mesh used

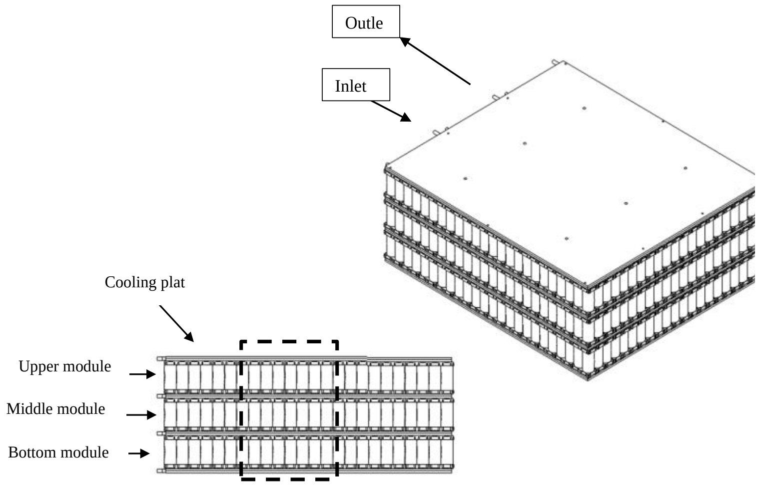


Figure 2. The battery configuration analyzed in the research used

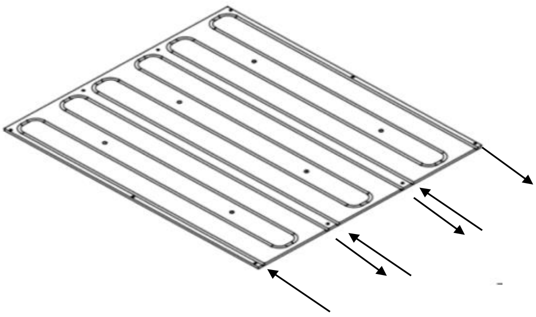


Figure 3. Cooling plates configuration

3. RESULTS AND DISCUSSION

Research conducted by numerical simulation on BTMS with liquid-cooled indirect has used fluid in the water. By using a simplified battery module using a 7×7 pattern, this module will describe the phenomenon of battery heat from the inner area to the outer area [13]. The resulting heat generation characteristics are instantaneous heat on the surface of the battery module used. The battery is an LFP-type battery with a stable heat generation character. The heat generated tends to be on the positive and negative poles used in the circuit. A battery with a higher discharge value will also have a higher heat value.

- Heat increases due to C-rate

The higher the C rate used, the higher the heat generated. It is caused by differences in internal resistance (IR) values due to heat generation. The higher the IR value will affect the heat generated. In the case carried out in this study, the higher the C rate, the higher the heat generated. It increases the potential for TR presence. The effect of the difference in the C-rate used is shown in Figure 4.

The discharge rate affects the heat generation rate; the higher the discharge rate, the more the heat generation rate increases. It affects the battery's temperature and then impacts the working efficiency of the Li-ion battery. This study has investigated the influence of different discharge rates. Five variations of discharge rates ranging from 0.5C to 3C were applied to batteries. At 1, 2, and 3C, show an increase in the average temperature in the battery along with changes in flow time with the highest heat temperature in the middle module area. It is caused by the cooling plates used will receive heat from the top and bottom of the battery module. The proposed design still produces good generation characteristics, indicated by the temperature used, which has an average value that remains in the normal working temperature area between 30 ºC when using a fluid flow of 1 m/s. The difference in the value of the inlet speed also affects the heat generated in the battery pack. When the velocity of the water flow is higher, the potential for absorption is also better, but further research regarding how long the cooling system is optimal needs to be taken into account. Table 3 shows that heat tends to be higher in the middle module area. This can be seen in the various discharge rates used. Compared to air coolers, this type of cooler can provide better heat distribution because the heat absorption capacity is more even when compared to air coolers.

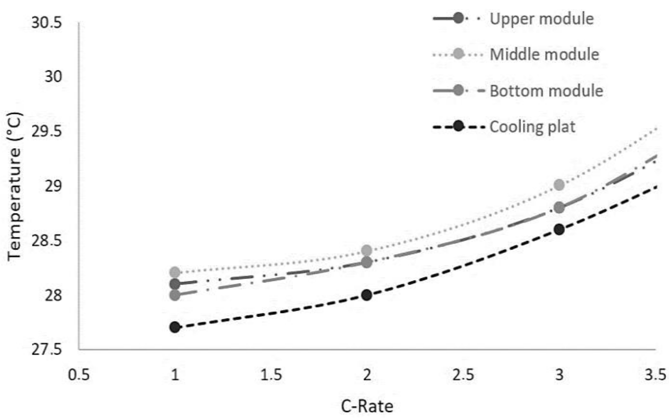
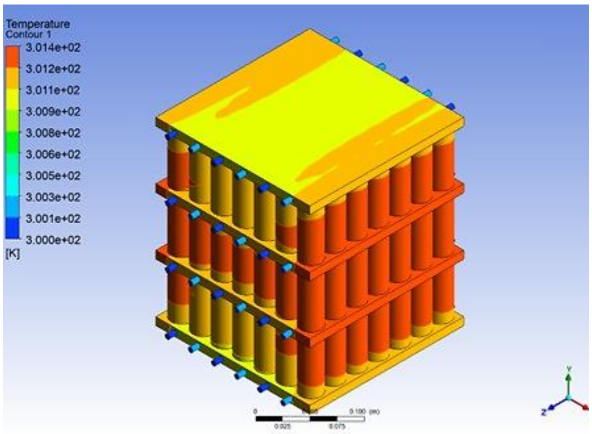


Figure 4. Heat at various C-rate

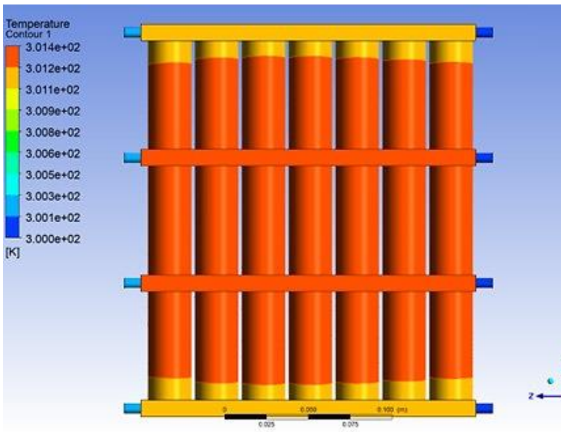
Table 3. Temperature differences in various battery pack segments

Position	Inlet speed (m/s)				Position	Inlet speed (m/s)			
	1	2	3	4		1	2	3	4
Upper module 0.5C	28.1	28.1	28	28	Upper module 2C	28.8	28.7	28.7	28.6
Middle module 0.5C	28.2	28.2	28.1	28.1	Middle module 2C	29	29	29	28.9
Bottom module 0.5C	28	28.1	28	27.9	Bottom module 2C	28.8	28.7	28.7	28.5
Cooling plates 0.5C	27.7	27.7	27.6	27.6	Cooling plates 2C	28.6	28.4	28.3	28.3
Upper module 1C	28.3	28.2	28.2	28.1	Upper module 3C	29.7	29.6	29.4	29.4
Middle module 1C	28.4	28.3	28.3	28.2	Middle module 3C	30.1	30	29.9	29.9
Bottom module 1C	28.3	28.3	28.1	28	Bottom module 3C	29.8	29.5	29.4	29.4
Cooling plates 1C	28	28	27.9	27.8	Cooling plates 3C	29.4	29.3	29.1	29.1

The heat generated has fairly even characteristics. The temperature difference on the surface of the battery is below 0.5 °C, so the heat distribution generated due to heat absorption on the cooling plates is quite good. The potential use of cooling plates still requires further development. Different inlet streams do not affect the heat absorbed by the cooling plates, which is caused by the absorption capacity of the same cooling plates when they have different inlet speeds. Look at Figure 5. The heat distribution on the battery module tends to be evenly distributed in all areas of the module used. Figure 5(a) shows the isometric location of the battery when in use. The battery has a different tendency to heat on the side parallel to the direction of fluid flow and in areas not parallel to the direction of fluid flow. Areas parallel to the direction of fluid flow have an excellent cooling rate compared to the outer areas because they have more potential for heat absorption. Figure 5(b) shows the part that experiences the highest heat, which is the middle area of the battery.



(a)



(b)

Figure 5. The distribution of the generated heat: (a) isometric view and (b) side view

4. CONCLUSION

The addition of liquid cool to the battery pack has considerable potential to maintain the performance of the battery pack. Batteries with type 26650 have enough space to be applied together with liquid cooling. Tests using water-cooled at various C-rates are applied to the battery's heat generation rate. This analysis concludes that the heat generation that occurs can be sufficiently reduced by using indirect liquid cooling. The battery used has three modules assembled into the same pack. Heat tends to collect in the center of the battery pack. It is caused by the cooling plates absorbing heat in the top and bottom areas with a heat difference below 0.5 ºC. Variations in the discharge rate of 0.5C, 1C, 2C, and 3C affect the battery's heat generation rate. The higher the rate of heat generation in the battery, the average temperature of the battery increases. The supply of fluid entering the cooling plates does not significantly affect cooling performance, with the average heat still at normal temperature, around 30 ºC.

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